**P3.10      The Origin of Monsoon Onset. Part II: Rotational ITCZ Attractors**

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## 1. Introduction

Through various specially designed numerical experiments with an aqua-planet general circulation model and theoretical arguments, Chao (2000, Part I of this work, hereafter C00) showed the existence of multiple quasi-equilibria of the intertropical convergence zone (ITCZ). He also showed that monsoon onset could be interpreted as an abrupt transition between the quasi-equilibria of the ITCZ. He further showed that the origin of these quasi-equilibria is related to two different types of attraction (or, "forces" as called in C00) pulling the ITCZ in opposite directions. One type of attraction on the ITCZ is due to earth's rotation, which pulls the ITCZ toward the equator or two equatorial latitudes symmetric with respect to the equator depending on the choice of convection scheme, and the other due to the peak of the sea surface temperature (SST, which is given in the experiments a Gaussian profile in latitude and is uniform in longitude), which pulls the ITCZ toward a latitude just poleward of the SST peak. The strength of the attraction due to the earth's rotation has a highly nonlinear dependence on the latitude and that due to the SST peak has a linear (at least in a relative sense; see C00 for discussion) dependence on the latitude.

Fig. 1 (same as Fig. 8.a of C00) shows these two types of attraction when Manabe's moist convective adjustment (MCA) scheme is used in the model. Curve R (positive means southward) is the attraction due to earth's rotation and line S (positive means northward) is the attraction due to SST peak when the SST peak is just south of the latitude where line S intersects the x-axis. Line S intersects curve R at three places. These are the quasi-equilibria; the outer two are stable and are the two possible locations for the ITCZ. When the SST peak is close to the equator, or when line S is replaced by line S1, there is only one quasi-equilibrium (point A in Fig. 1) which is on the equator side of the SST peak. Point A moves poleward at a slower rate, when the SST profile is moved poleward while maintaining its Gaussian shape. As the SST profile is moved poleward, line S moves poleward and (more or less) keeps its slope, quasi-equilibria B and C appear but the state

remains at A. As the SST peak continues to gain latitude it will come to a point that point A disappears and the state (or the ITCZ), being pulled by the difference between curve R and line S, moves rapidly toward point C. Such a rapid change of latitude of the ITCZ was interpreted in C00 as monsoon onset. The shape of curve R was confirmed by experiments; see Figs. 10 and 11 of C00 and their associated discussions. The counterpart diagram when the relaxed Arakawa and Schubert scheme (Moorthe and Suarez 1992, hereafter RAS) is used, should instead be represented by Fig. 2. Curve R is now represented by two curves in the lower latitude part of the tropics and is represented by one curve in higher latitudes.

There are two important experimental facts discovered but unexplained in C00. One is the shape of curve R, or the highly nonlinear nature of the dependence of curve R on latitude. When MCA is used, curve R, shown in Fig. 1, rises from zero at the equator with the latitude, reaches a maximum at about 8 or 9 degrees N, drops rapidly to near zero at about 14 N and then again rises sharply northward at a rate much higher than that at the equator. It is antisymmetric with respect to the equator. It is this highly nonlinear dependence that makes the multiple quasi-equilibria of the ITCZ and monsoon onset possible. The other unexplained fact is the drastic difference in the shape of curve R when different cumulus parameterization schemes are used (i.e., the different shape of curve R in Figs. 1 and 2). When RAS is used, curve R, also deduced experimentally, has different structure. Because of the different shape of curve R the model gives (as reported in C00), when SST is globally uniform (i. e., line S is zero), the intersects of curve R and line S (or the x-axis) give a single ITCZ at the equator in the case of the Manabe scheme and a double ITCZ in the case of RAS (Fig. 1 of C00.) This feature remains when the SST takes on a Gaussian shape and its peak is not too strong (i. e., the slope of line S is not too high) and is in the equatorial region. These are very different results. The purpose of this paper is to investigate these two puzzles.

## 2. Model used

The Goddard Earth Observing System general circulation model version 2 (GEOS-2 GCM) with 4° (lat.) by 5° (lon.) grids and 20 levels is used. This is an updated version of the model used in Part I. The details of the model is given in Chao and Chen (2001).

## 3. Interpretation

We can consider the locations of 13 degrees N and S as the centers of two attractors pulling on the ITCZ due to earth's rotation when the SST and the solar angle are uniform (which we name the rotational ITCZ attractors). The attraction (or the "force" as explained in C00) due to each attractor on the ITCZ is shown in Fig. 5 with positive values being southward. The "force" (or attraction) is zero at the center of the attractor and has different signs on the two sides of the center. The magnitude of the "force" reaches a peak at some distance away and then falls at greater distance. The rise of the "force" from zero at the center of the attractor is assumed to be of sinusoidal type and the fall at greater distance is assumed to be of exponential type. These are reasonable assumptions, in the sense that deductions based on these assumptions fit experimental results. Theoretically, these assumptions are reasonable because the "force", due to the finite size of the attractors, has to diminish at greater distance. Although we can say that the scale of the attractors (or, the latitudinal distance from the center of the attractor to where the "force" is the largest) has something to do with the vigor of convection, exactly what determines it still awaits more theoretical work.

If the peak of the attraction is located in the same hemisphere as the center of the attractor, the combination of the two attractors gives an unstable quasi-equilibrium at the equator. That means a single ITCZ at the equator can not exist. This is the situation of Fig. 2. The sum of Rs and Rn has a negative slope or an unstable equilibrium at the equator. If the attractors become stronger and wider or if the centers of the attractors move closer to the equator (say, when a different cumulus parameterization scheme is used, when some parameters in the scheme are tuned, or when some features in the model outside of the cumulus parameterization scheme are changed), the "force" peak location can be moved to the other side of the equator. The situation can change to give curve R a shape shown in Fig. 1, which has a stable quasi-equilibrium at the equator. Fig. 3 shows such a combination. In

other words, the two rotational ITCZ attractors away from the equator merge into one centered over the equator. In Fig. 3 the slope of curve R at the equator is the same as the slope of the "force" at the equator due to either attractor. The latter is smaller than the slope of the "force" at the center of either attractor. Due to the rapid decline of the "force" due to the 13S attractor south of 13N, at 13N the slope of curve R is almost the same as that of the 13N "force" at its center. This is consistent with the experimental fact that the rise of curve R north of 13N is greater than its rise at the equator. The sum of the two "forces" after reaching a peak around 7N drops quickly poleward to give curve R a shape like what is shown in Fig. 1. Numerical experiment results will be presented in the next section to support this idea.

## 4. Supporting numerical experiments

According to the idea in the preceding section, it is possible to make changes in a cumulus parameterization scheme and obtain a change in the experimental outcome from one depicted by Fig. 2 to another depicted by Fig. 1 or vice versa. This will result in a change in the stable quasi-equilibria, or a change between double ITCZ (or a single ITCZ away from the equator) and a single ITCZ at the equator. We will make a change in RAS, which is an addition of a condition to be met before cumulus convection is allowed to occur. The condition is that the boundary layer relative humidity has to be greater than a critical value, $r_c$. Raising $r_c$ gives a more intense ITCZ (because cumulus convection becomes harder to occur, and when it does occur it is more intense) and the rotational attractors become stronger and their "force" peaks (in absolute value) can cross the equator (starting from curve RS or RN in Fig. 2). The shape of curve R can change from that of Fig. 2 to that of Fig. 1 and correspondingly the two off-equator stable ITCZ quasi-equilibria change to one at the equator.

Fig. 4 shows the zonal mean precipitation averaged over the last 100 days of three 455 day experiments using RAS with uniform SST of 29°C with $r_c$ equal to 0%, 90% and 95%. The initial conditions are the same as those in C00 and the solar angle is the globally averaged value. In the first two experiments the curve R has the shape of Fig. 2 and the third experiment curve R has the shape of Fig. 1. Fig. 5 shows the ITCZ location of an experiment with

uniform SST of 29°C where RAS is used and $r_c$ is increased from 90% to 95% linearly in 100 days after a period of 200 days with $r_c$=90%. The ITCZ that starts out being away from the equator switches to the equator in a short period of 30 days. Fig. 6 is an identical experiment except the $r_c$ values of 90% and 95% are switched. The ITCZ that starts out at the equator switches away from the equator; the switch in this case is much faster, almost instantaneous around day 250. The equatorial ITCZ regime in Figures 5 and 6 shows occasional split into double ITCZ structure (e.g., day 112 through day 160 in Fig. 6). However this structure, in which the ITCZ's are only 6 or 7 degrees away from the equator, is distinctly different from the ITCZ in the other regime (of rc=90%) where the ITCZ is 13 degrees away from the equator and exists in only one hemisphere. In the equatorial ITCZ regime there are also weaker rain bands located at 19-23 degrees in both hemispheres which oscillate in time with an intraseasonal periodicity (which are reflected in the dash line in Figure 4) and are weaker when the ITCZ at the equator becomes stronger. Although the reason for such a flow regime remains to be investigated, this result reveals the complexity and richness of the interaction between convection and large-scale circulations and the need for further refinement of our theory. The framework of this refinement is that the rotational ITCZ attractors we proposed should be considered as quasi-equilibria (as stated in C00) instead of fixed point attractors. Thus there can be small oscillation in time of the location, strength and shape of the attractors and it is these small oscillations that give rise to a variety of complex flow patterns.

We have made attempts to modify the model such that the model running with MCA can generate double ITCZ. Our attempts have not been successful. However, in one experiment with uniform SST where surface friction is removed, the single ITCZ over the equator is much broader, indicating that the slope of Curve R at the equator has become smaller. This is consistent with the moving apart of the rotational ITCZ attractors.

Chao and Chen (2001) gives A more detailed version of this paper.

**References**

Chao, W. C., 2000:. *J. Atmos. Sci.*, 57, 641-651.

Chao, W. C. and B. Chen, 2001: *J. Atmos. Sci.*, to appear.

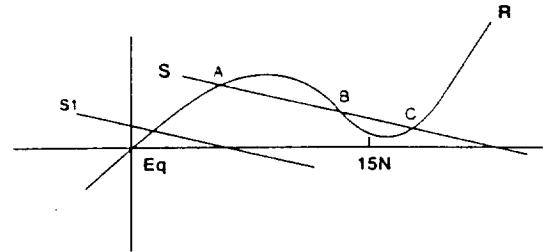Moorthi, S., and M. J. Suarez, 1990: *Mon. Wea. Rev.*, 120, 978-1002.



Fig.1. Schematic diagram showing the two "forces" acting on the ITCZ when the Manabe scheme is used in the model. Curve R represents the "force" due to earth's rotation (positive means southward). Line S represents the "force" due to the SST (positive means northward). The SST has a Gaussian shape in latitude and is uniform in longitude and is given in Eq. (1) of C00.
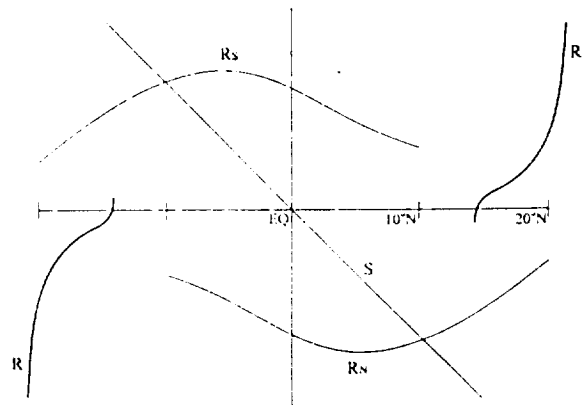


Fig. 2. Same as Fig. 1 but for RAS. RN and RS are the "forces", positive being southward, due to the rotational attractors in northern and southern hemisphere, respectively. The thick curve R is for the combined "forces" of the two rotational attractors in the single ITCZ regime. Line S denotes the "force", positive being southward, due to the SST profile when the SST peak is at the equator.
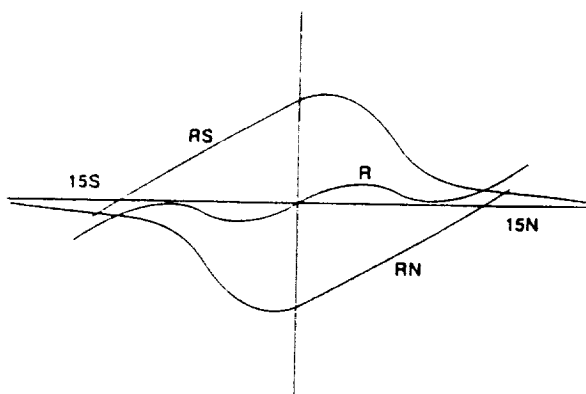
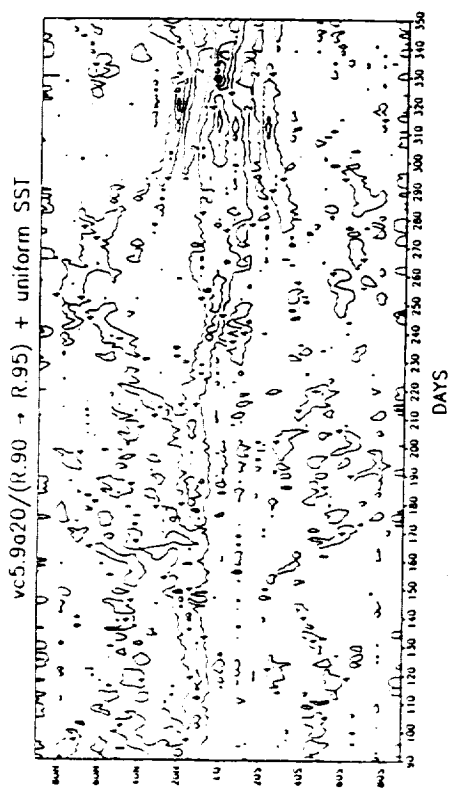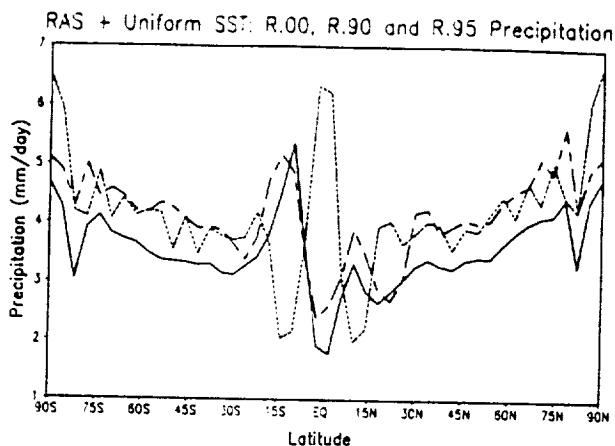Fig. 3. The combination, R, of two rotational ITCZ attractors, RN and RS, with large domain of influence.



Fig. 4. Zonal mean precipitation averaged over the last 100 days of three 455 day experiments with uniform SST of 29°C and with the condition of boundary layer relative humidity being greater than 0% (solid), 90% (long dash) and 95% (short dash) imposed on RAS.
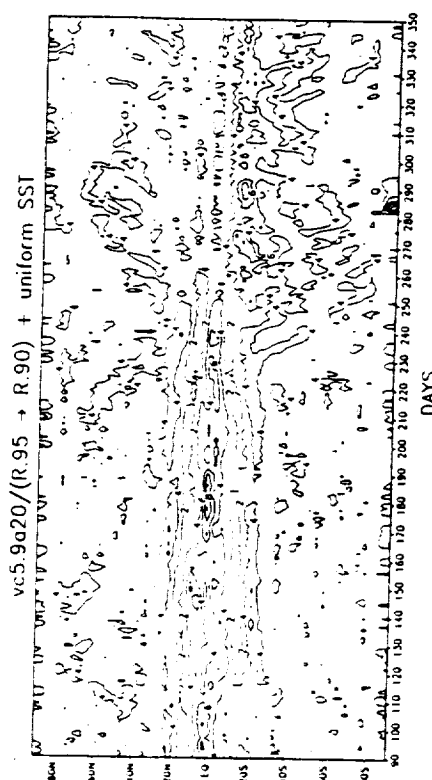


Fig. 5. Position of the ITCZ of an experiment with uniform SST using RAS and $r_c$ is increased from 90% to 95% linearly in 100 days after a period of 200 days with $r_c$ =90%. $r_c$ is the critical boundary layer relative humidity value above which cumulus convection is allowed.



Fig. 6. Identical to Fig. 5 except the values of $r_c$ =90% and 95% are switched.